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Cold War on a Warming Planet: Climate Policy in a Divided World

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Cold War on a Warming Planet: Climate Policy in a Divided World

January 14, 2026

Lucas Bretschger¹

Abstract

The study examines economic growth and climate change when system competition between countries causes drastic changes in their climate policies. The world is divided into two groups of countries: one that implements strict climate policies and another that refrains from doing so due to concerns about the negative economic impacts. A policy tipping point occurs once the economic performance of the proactive group surpasses that of the laggards, prompting the latter to implement comparable climate measures. I find that the impact of policy tipping is significant on emissions but moderate on economic growth. The occurrence of the policy shift depends on policy design and technological progress. In a divided world, subsidies for clean energy research prove more effective than carbon pricing in accelerating global decarbonization because they induce earlier tipping. Achieving the internationally agreed climate targets requires that proactive countries combine ambitious emissions reductions with sustained economic prosperity, an outcome attainable through an efficient mix of taxes and subsidies.

Keywords: Carbon policy; divided world; economic growth; global carbon emissions; policy tipping.

JEL Classification: Q43, O47, Q56, O41

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1 Introduction

The concept of the social optimum constitutes a cornerstone of economic theory. It underpins the analytical framework for optimal climate policy, which seeks to address the market failures associated with greenhouse gas emissions. According to conventional economic reasoning, experts identify the socially optimal policy and provide guidance to policymakers and the electorate, who subsequently enact it through political mechanisms. Yet, recent experience has demonstrated that this process proves highly challenging even within national contexts, let alone at the international level, where nearly 200 sovereign states must coordinate and reach consensus on shared policy principles. It is true that in recent decades, the international community has undertaken significant collective efforts to reduce negative externalities and promote sustainability at the global level. Landmark agreements, such as the United Nations Sustainable Development Goals and the Paris Climate Agreement, represent major diplomatic achievements. However, the actual implementation of effective sustainable development programs and stringent climate policies has proven challenging. Under the current administration, the United States, one of the world’s largest greenhouse gas emitters, has shifted from active participation in global climate frameworks to an open rejection of comprehensive climate policy,² a stance that some other, mostly oil-producing countries share, albeit often expressed less explicitly.³ In today’s fragmented international landscape, several influential states refrain from making adequate contributions toward achieving the internationally agreed temperature targets. The other countries remain politically committed to implementing climate policies determined by international climate agreements. The principles of the social optimum hold limited practical relevance for either country group.⁴

The international confrontation between two different assessments of climate policy reflects two competing economic paradigms, an extractive model versus a sustainability approach.⁵ The tension between these paradigms has become evident in recent global eco-

²In 2025, the United States withdrew for a second time from the Paris Agreement under the United Nations Framework Convention on Climate Change (Congressional Research Service 2025)

³At the COP 30 in Belém 2025, main oil-producing countries like Saudi Arabia and Russia resisted including a binding roadmap to phase out fossil fuels in the final declaration.

⁴Several climate economic models have calculated an optimal warming that deviates from the internationally agreed temperature targets, which remains to be the guideline for the country group undertaking active climate policies; in the other country group, the mere existence of negative externalities has been challenged publicly. In his speech to the United Nations General Assembly on 23 September 2025, the American President outright dismissed climate change scientific consensus and claimed the concept of a “carbon footprint” is a hoax fabricated by “people with evil intentions” (National news 2025).

⁵The extractive model privileges short-term economic expansion while externalizing ecological costs, which has historically supported industrialization, poverty reduction, and economic growth. The second

conomic discourse.⁶ Historically, geopolitical rivalries, whether between monarchies, nation-states, or ideologies, have shaped world order. The Cold War epitomized this dynamic, with competition between the capitalist Western Bloc and the communist Eastern Bloc manifesting in economic and technological arenas. The inefficiency of planned economies, coupled with technological stagnation, contributed to the dissolution of the Soviet Union in 1991 ending the cold war.⁷ Today, we experience a revival of a division with respect to economic and political systems, in particular - but not exclusively - with climate policy.⁸ The heated rhetoric characterizing recent climate policy debates recalls certain features of the Cold War era of the last century. Whether countries will rapidly converge again toward a common ecological framework remains highly uncertain. It is thus possible that a period of conflict between competing economic systems will precede the establishment of a new global order. History suggests that economic systems ultimately evolve when existing models become inferior. The economic gap between the Eastern Bloc (the Soviet Union and its allies) and the Western world before the USSR's collapse was large,⁹ and the consequences of the collapse were equally large. In the context of environmental protection, a comparatively smaller gap in economic performance could be sufficient to trigger a shift in the adoption of climate policy, having significant consequences for climate change.¹⁰ Worldwide, climate change has lost some of its political priority, but the state of the economy and the costs of climate policy remain a top concern. Hence, if the governments of lagging countries recognize that other countries are deriving net economic benefits from climate policy, their attitude toward adopting a policy is likely to change.

paradigm, grounded in sustainability and environmental stewardship, highlights resource efficiency, low-carbon transitions, and renewable energy adoption, which may foster innovation, resilience, and long-term development.

⁶At the United Nations, the American President argued that renewable energy initiatives are economically harmful. For example, he said they cause manufacturing and industrial activity to move from countries that adopt strict rules to those that don't. He mocked renewable energy, calling it "a joke" and "too expensive," and contrasted it with his support for fossil fuels and what he called "clean, beautiful coal." He criticised European nations, saying that their green-energy agendas and open-border immigration policies were leading them toward decline.

⁷For the time afterwards, Francis Fukuyama (1992) argued that the period of clashes and competition between systems was over, while Samuel Huntington's "Clash of Civilizations" theory (Huntington, 1996) suggested that conflicts would continue, mainly driven by cultural divisions.

⁸At the United Nations, the American President further attacked countries fostering decarbonization and energy transition by saying "If you don't get away from this green scam, your country is going to fail." This and similar statements suggest to draw a parallel to the Cold War and to extract the expected "failure" of countries with active environmental policies as a main justification for an extractive attitude (National news 2025).

⁹Approximate GDP per capita (1988–1990, in 1990 international Geary-Khamis dollars, PPP-adjusted): United States, \$23,000, Western Europe (average), \$18,000–22,000, Eastern Europe (average) \$7,000–9,000

¹⁰A recent example of a policy shift driven by economic performance is the U.S. government's removal of tariffs on several important goods.

This paper uses a macroeconomic climate model with endogenous innovations, determining economic growth and emissions development. It considers a world economy that is divided into two groups of countries. The first "extracting" group favors natural resource use and refrains from implementing climate policies, based on the belief that climate change is not a major problem and that climate policy has adverse economic effects; the second "protecting" group implements policy to achieve the internationally agreed temperature targets. The paper makes three contributions to the literature. First, it characterizes decarbonization and economic growth for each group separately and calculates the effects on global emissions, in particular the delay in emissions reduction caused by the extracting countries. Second, the model derives how economic growth and global emissions change when systems competition between the country groups triggers a change in climate policies. Specifically, the paper looks at the case where, at a certain point in time, the economic performance in the protecting group surpasses that in the extracting system, inducing a policy change in the latter. This specific kind of policy tipping is triggered by general economic performance and not simply by a comparison of energy prices of clean and dirty, because the two energy types are imperfect substitutes.¹¹ Third, the paper analyzes the effects of possible policy responses by the protecting group, given the lacking policy commitment of the extracting countries.

Policy convergence after a tipping point represents only one, though potentially very important, scenario for future development. A highly optimistic, albeit probably less realistic, alternative perspective envisions all countries rapidly resuming cooperative efforts to meet the global climate targets under the UN Convention. However, in an increasingly selfish and fragmented world, it is becoming more and more difficult to convince certain countries to contribute to the global common good. Economic arguments appear to be more suitable to change their minds, which is the motivation of this article. Conversely, a pessimistic scenario assumes that an increasing number of countries lose faith in global cooperation and join the extracting system. The present contribution represents an intermediate scenario, describing a policy in extractor countries that is framed exclusively by economic factors and not by any environmental concerns. The growing attractiveness of regenerative energies under market conditions, supporting green policies in the protecting group, and policy tipping in the extractor group will be the driving forces of decarboniza-

¹¹The importance of relative energy prices is highlighted in a statement of former VP Al Gore who said: "the big change is that people are way more receptive... they've now developed the solutions to the point where they're available and often cheaper than the old dirty polluting fuels. So we're winning this debate .. we're going to solve the climate crisis." (CBS news 2017)

tion in the model. Active climate policies in extractor countries could also be triggered by a drastic increase in climate damages, though such a response is likely to come too late to prevent severe additional disasters.

The present paper is related to various strands of environmental and, in particular, climate economics in the context of endogenous innovation. How different forms of technical change affect economically optimal emission trajectories has been covered in great detail by Coppens, Dietz, and Venmans (2025). The macroeconomic modelling of climate change and optimal climate policy has been developed in Golosov et al. (2014), Dietz and Stern (2015), Nordhaus (2016), Brock and Xepapadeas (2017), Bretschger and Karydas (2019), Withagen (2022), and Schubert et al. (2026). The impact of knowledge build-up and spillovers on the energy transition has been analyzed by Smulders and de Nooij (2003), Hart (2013), Acemoglu et al. (2016), Greaker et al. (2018), Creti et al. (2018), Hart (2019) and Bretschger (2024). The endogenous elasticity of substitution between clean and dirty energy used in the paper is due to Jo and Miftakhova (2024). The mechanism of innovation-driven endogenous growth is based on Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992); it has been combined with natural resources in Barbier (1999) and Peretto and Valente (2024, 2025). The present paper is anchored in this field and adds the aspects of a divided world, system competition, and potential policy shifts to the literature. Politically determined taxes have been used in the stochastic literature by Bretschger and Soretz (2022), while the present contribution uses a deterministic approach that is applied to climate policy.

The remainder of the paper is organized as follows. Section 2 develops the model and derives the decentralized equilibrium. Section 3 derives the theory results. In Section 4, the model is used for an extensive quantitative analysis. Section 5 discusses model extensions and their impact, while Section 6 concludes.

2 Model

2.1 Overview

I consider two groups of countries. The first group prioritizes the extraction of natural resources without implementing policies to correct for the externalities of resource use; I refer to this as the “extractor” group, denoted by R . The second group imposes taxes on environmental pollution in order to meet internationally agreed temperature targets; this is the “protector” group, denoted by Q . Each group generates and consumes its final

output. To focus on the specific impact of asymmetric climate policies, production in the two groups is symmetric i.e. the parameters characterizing the production process in the energy sector and the rest of the economy are assumed to be identical across groups. Unequal environmental policies cause uneven development of the two groups, which induces policy tipping in group R when economic performance in group Q becomes superior. I posit that governments and voters perceive economic growth as a valid measure of economic performance.¹²

2.2 Households

In each group j , $j = R, Q$, households derive utility from consumption C_j and disutility of global pollution stock P ;¹³ they maximize intertemporal utility U according to

$$U_{jt} = \int_0^{\infty} e^{-\rho t} [\log C_{jt} - P_t] dt \quad (1)$$

where ρ is equal to the pure time preference rate. Agents own wealth V_{jt} in the form of physical capital and stocks of fossil; each household offers one unit of labor to the labor market at wage rate w , receives revenues from selling fossil energies E_{Dj} at prices p_{Dj} and consumes final goods in the amount of $p_{Cj}C_j$. The dynamic budget constraint is

$$\dot{V}_{jt} = r_{jt}V_{jt} + w_{jt} + p_{Dj}E_{Dj} - p_{Cj}C_{jt}. \quad (2)$$

where a dot denotes the derivative with respect to time and r is the interest rate.

2.3 Energy and emissions

In both groups $j = R, Q$, energy firms combine two types of energies, fossil and regenerative, labelled "dirty" energy E_{Dj} and "clean" energy E_{Cj} , to supply energy E_j at market price p_{Ej} to their own market.¹⁴ Below, the time index will be omitted whenever there is no ambiguity. Energy output in group j reads

$$E_j = \left[\varphi E_{Dj}^{\frac{\sigma_j-1}{\sigma_j}} + (1-\varphi) E_{Cj}^{\frac{\sigma_j-1}{\sigma_j}} \right]^{\frac{\sigma_j}{\sigma_j-1}} \quad (3)$$

where σ_j is the elasticity of substitution between clean and dirty energy in j . Minimization of the costs in the energy sector yields the optimal ratio between dirty and clean energy as

¹²One might also pick the income level of the countries as a performance indicator but the analysis and the main conclusions would only change marginally.

¹³The model does not consider population growth so that aggregate consumption and individual consumption develop in the same manner.

¹⁴International trade in energy and consumer goods is disregarded for simplicity, see the separate remarks below and in the discussion section.

a function of relative input prices, p_{Dj} and p_{Cj} , according to

$$\frac{E_{Dj}}{E_{Cj}} = \left(\frac{\varphi}{1-\varphi} \right)^{\sigma_j} \left(\frac{p_{Dj}}{p_{Cj}} \right)^{-\sigma_j} \quad (4)$$

and relative factor shares as

$$\frac{\theta_j}{1-\theta_j} = \left(\frac{\varphi}{1-\varphi} \right)^{\sigma_j} \left(\frac{p_{Dj}}{p_{Cj}} \right)^{1-\sigma_j} \quad (5)$$

where

$$\theta_j = p_{Dj}E_{Dj}/p_{Ej}E_j \quad (6)$$

$$1-\theta_j = p_{Cj}E_{Cj}/p_{Ej}E_j. \quad (7)$$

Building on the empirical results of Jo and Miftakhova (2024), the substitution elasticity σ is a (positive) function of clean energy use, according to¹⁵

$$\sigma_{jt} = 1 + \beta(1-\theta_{jt})^\gamma \quad (8)$$

where $\beta, \gamma > 0$. Energy price growth \hat{p}_E is given by¹⁶

$$\hat{p}_{Ejt} = \theta_{jt}\hat{p}_{EDjt} + (1-\theta_{jt})\hat{p}_{ECjt} \quad (9)$$

where hats denote growth rates and \hat{p}_{EDj} and \hat{p}_{ECj} the price growth of energy type D and C in j . Fossil energy E_{Dj} is extracted from resource stocks, which are privately owned by the households. Clean energies E_{Cj} are generated by exploiting publicly available resources like sun and wind \tilde{E}_{Cj} with productivity B , i.e.

$$E_{Cj} = B_j\tilde{E}_{Cj}. \quad (10)$$

Further inputs in the energy conversion and the effects of resource scarcities in clean energies are disregarded for the sake of brevity; they would equally apply to both country groups and thus not affect our core results on system competition.¹⁷ The conversion cost of \tilde{E}_{Cj} are strictly positive and affected by productivity B , which increases through learning and growing work experience in proportion to existing knowledge, i.e.

¹⁵The functional form used by Jo and Miftakhova (2024) reads $1 + \beta(E_C/E_D)$; here, the γ allows for more flexibility in calibration and, with given price paths for the energy types, the use of expenditure shares is equivalent to using energy quantities.

¹⁶See Jones (1965).

¹⁷Raw material scarcity in clean energy conversion is analysed in Chazel et al. (2022) and Pommeret et al. (2022). I accommodate the scarcity aspect here by adjusting the calibration of progress in renewable energies, see the quantitative section, and briefly discuss the theoretical aspects in the separate discussion section at the end of the paper.

$$\dot{B}_{jt} = \chi B_{jt} \quad (11)$$

where $\chi > 0$.¹⁸ Carbon emissions Z are proportional to the use of fossil fuels; with α denoting emission intensity of dirty energy ($Z = \alpha E_D$), they augment the stock of global greenhouse gases P_t according to

$$\dot{P}_t = \alpha \sum_{j=R,Q} E_{Djt} \quad (12)$$

where the decay rate of P is assumed to be zero for simplicity.

2.4 Policies and energy prices

Two policy instruments are available, carbon pricing and subsidies to clean energy research. Group Q taxes fossil energies from the beginning at a rate it deems appropriate to fulfill the internationally agreed temperature targets. In practice, fossil fuel prices are highly volatile. To obtain the targeted emissions reductions, governments in the Q group do not impose carbon taxes that are independent of market prices of fossils, p_{EDQ} , but rather directly set end-user prices of dirty energy, denoted by \tilde{p}_{EDQ} ; the actual carbon tax then amounts to $\tilde{p}_{EDQ} - p_{EDQ} > 0$. In view of the increasing scarcity of carbon space over time, they choose a growing \tilde{p}_{EDQ} , i.e. a constant growth rate of end-user prices, which is denoted by ω_Q . Subsidies to clean energy research s_χ raise research productivity χ . I start the analysis with no subsidies for clean energies in Q , i.e. $s_{\chi Q} = 0$, but derive their impact separately after the first set of results. Following the motivation of the paper, group R implements no subsidies to clean energy research, $s_{\chi R} = 0$, and imposes no tax on fossils, $\tilde{p}_{EDR} = p_{EDR}$, $\omega_R = 0$, before policy tipping. System competition between R and Q may change this policy choice of R , when Q becomes economically more successful, achieving a higher consumption growth rate than R . If it happens and tipping is active, R starts taxing fossil fuels as well, choosing $\omega_R > 0$.

Due to technical progress that raises productivity in the conversion of regenerative energies over time, the market price of clean energies is decreasing at the rate $-\hat{p}_{ECj} = \chi_j$.¹⁹ With prices of fossil energies and global pollution given for the individual household, the individual decision problem consists of maximizing Eq. (1) subject to Eq. (2) with C as

¹⁸International knowledge diffusion could be integrated as an extension of the baseline model, see the discussion section at the end.

¹⁹Way et al. (2022) report annual price drops of around 10 percent for solar and batteries in the last decades and project a similar pattern for the future.

control variable and V as state variable. The government collects carbon tax revenues and pays subsidies to clean energy research.²⁰

2.5 Final output

In each block $j = R, Q$, final output Y_j is assembled from heterogeneous intermediate goods, x_{ji} , according to the Spence-Dixit-Stiglitz model²¹

$$Y_j = A_j \left[\int_0^{N_j} x_{ji}^\varepsilon di \right]^{\frac{1}{\varepsilon}} \quad (13)$$

where $A_j > 0$ and $0 < \varepsilon < 1$. Output grows not only with increasing input quantities x_{ji} but also with rising product variety N_j . The x -goods are imperfect substitutes for each other, they are produced under the market form of monopolistic competition. Final good producers maximize profits, which are given by $p_{Y_j} Y_j - \int_0^{N_j} p_{ji} x_{ji} di$ so that the optimal price of x_{ji} is obtained by a markup over marginal costs \tilde{c}_{ji} , i.e. $p_{ji} = \frac{\tilde{c}_{ji}}{\varepsilon}$. In each group, a mass of N_j atomistic firms produces x -goods in quantity x_{ji} , $i \in [0, N_j]$, using labor L_j , capital K_j , and energy E_j as inputs, according to

$$x_{ji} = L_{xji}^a K_{ji}^b E_{ji}^{1-a-b} \quad (14)$$

where $0 < a, b < 1$.²² The Cobb-Douglas production function in Eq. (14) allows for substitution between energy and the other inputs but substitution is limited as energy is an essential input in production.²³ The x_j -firms maximize profits, which are given by $p_{ji} x_{ji} - w_{jx} L_{jxi} - p_{jK} K_{ji} - p_{jE} E_{ji}$ where p with a subscript denote prices and w_{X_j} the wage rate in the intermediate sector. First-order conditions for profit maximization of x -firms are given in the Appendix. For better tractability I use a symmetrical equilibrium where x -goods have equal production costs $\tilde{c}_{ji} = \tilde{c}_j$ so that $p_{ji} = p_j$, $x_{ji} = x_j$, and $Y_j = AN_j^{\frac{1-\varepsilon}{\varepsilon}} X_j$ where $X_j \equiv N_j x_j$. With this we obtain $p_{x_j} X_j = p_{Y_j} Y_j$ and $\tilde{c}_j X_j = \varepsilon p_{Y_j} Y_j$ while $(1 - \varepsilon) p_{Y_j} Y_j$ are the aggregate profits in the X -sector.

Given the monopolistic distortion, the demand functions for labor, capital, and energy

²⁰ A formal budget constraint for the government is not introduced but could be studied in an extension of the model.

²¹ Dixit and Stiglitz (1977)

²² Marginal costs \tilde{c}_t can be derived formally from Eq. (14), output elasticities of the production function are identical to the cost shares of the inputs in the cost function.

²³ In the past, oil shocks had transitional positive effects on the energy expenditure share which reflects a complementarity between energy and capital in the short run. The decoupling of energy from income and capital in countries like Sweden, UK, and Switzerland shows that an elasticity of unity between energy and the other inputs is a valid assumption for the longer time horizon, which is considered here.

can be written as

$$w_{Xj} = \frac{\varepsilon a p_{Yj} Y_j}{L_{Xj}} \quad r_{jt} = \frac{\varepsilon b p_{Yj} Y_j}{K_j} \quad p_{Ej} = \frac{\varepsilon(1-a-b)p_{Yj} Y_j}{E_j}, \quad (15)$$

where L_{Xj} , K_j , and E_j stand for group j 's demand for these inputs, i.e., $L_{Xj} = N_j L_{xj}$, where L_{xj} is the demand of a single firm that is equal across all firms. K_j , and E_j are defined analogously.

2.6 Variety expansion

Following Romer (1990) and Grossman and Helpman (1991) I assume that the expansion of intermediate goods varieties N and the associated gains from diversification drive long-run economic growth. Knowledge generation uses skilled labor H as an input. Labor L can be transformed into skilled labor through on-the-job-training, which requires part of total worktime. When labor devoted to research is L_N , skilled labor becomes $H = \kappa \cdot L_N$ with $0 \leq \kappa < 1$. Knowledge creation receives spillovers from existing knowledge stock, which is - by appropriate normalization - equal to the number of existing product varieties N . The intensity of the knowledge spillover is measured by the parameter ψ , $0 < \psi \leq 1$, reflecting the speed of knowledge diffusion and adoption. Given the importance of implicit knowledge in modern production and the constant demand from companies for specific knowledge, e.g., in the field of IT, I abstract from introducing patents in the model. I rather posit that a new firm requires not only new knowledge for market entry but also a continuous inflow of knowledge to sustain operations thereafter. Because firm-specific knowledge is neither protected as private property nor separable from knowledge work, the research sector's share of turnover flows entirely into skilled labor in the knowledge sector. However, only one x -firm produces a variety at the time, as a second company would face the same production cost but would have to pay again for the knowledge services. Two companies would never be able to fully recover their knowledge costs in Bertrand competition and would therefore suffer losses, leaving only one company per x -good to survive.

With $m > 0$ denoting the productivity of labor in research, the increase in knowledge i.e. the number of varieties is given by

$$\dot{N}_j = m \kappa \psi L_{Nj} N_j \quad (16)$$

where L_{Nj} is labor devoted to research in the intermediate goods sector.²⁴ Current profits

²⁴For the case of knowledge production being adversely affected by climate change, see Bretschger and Komarov (2024).

in the aggregate X -sector are used for the firms' payments of knowledge input, i.e.

$$(1 - \varepsilon)p_{Yj}Y_j = p_{Nj}N_j \quad (17)$$

where p_N is the market price of knowledge service per firm. Research firms pay research labor a wage rate w_N equal to the marginal productivity of research labor; it is obtained by taking the derivative of Eq. (16) with respect to research labor L_{Nj} , multiplied by p_{Nj} , and using Eq. (17) to write

$$w_{Nj} = m\kappa\psi(1 - \varepsilon)p_{Yj}Y_j. \quad (18)$$

2.7 Labor market

Labor is employed in two sectors: the production of intermediates and the research to invent new intermediate goods varieties. Labor is fully mobile within a country group, so that wages are equal across the sectors of a group; the equilibrium wage is $w_{Xj} = w_{Nj} = w_j$. The labor market clearing condition in j becomes

$$L_j = L_{Xj} + L_{Nj} \quad (19)$$

where L_j is total labor supply in j . To ease the notation, I normalize each group's labor force to unity, i.e. $L_j \equiv 1$.²⁵ Labor demand in intermediates depends positively on final goods sales and negatively on the wage rate

$$L_{Xj} = \frac{b\varepsilon p_{Yj}Y_j}{w_{Xj}}. \quad (20)$$

Inserting wages from Eq. (18) in Eq. (20) yields

$$L_{Xj} = \frac{b\varepsilon}{m\kappa\psi(1 - \varepsilon)} \quad (21)$$

which is constant over time. In each group j , employment in the intermediates' sector grows with the labor share b and the revenue share that is not attributed to profits, ε .

3 Results

I start by presenting results on energy shares and prices to prepare the ground for the main topic of the potential policy shift in group R . With energy prices that are determined by technical progress and policies, the expenditures for the two types of energies as a share of total energy expenditures are a suitable indicator for the state of decarbonization. The

²⁵The model avoids assuming that the number of scientists is fixed, which is often posited in models of directed technical change.

baseline model assumes carbon pricing in Q but not in R and abstracts from research subsidies, i.e. we have the policy set $\omega_Q > 0$, $\omega_R = 0$, $s_{\chi Q} = s_{\chi R} = 0$.

We can state

Lemma 1 *In both country groups R and Q , growth of the the expenditures for fossil energies as a share of total energy expenditures is negative and an exponential function of the share of clean energies; in the protector group Q , the share decreases faster for any given share θ_j and at any point in time t .*

Proof. Take the logarithmic differential of Eq. (5) and use Eq. (8) as well as the group-specific growth rates of energy prices to obtain

$$\hat{\theta}_{Rt} = -\beta (1 - \theta_{Rt})^{1+\gamma} \chi \quad (22)$$

$$\hat{\theta}_{Qt} = -\beta (1 - \theta_{Qt})^{1+\gamma} (\omega_Q + \chi) \quad (23)$$

where $\beta, \gamma > 0$ and $0 < \theta_{jt} < 1$ so that the expressions on the right hand sides of Eqs. (22) and (23) are negative. Because of $\theta_{Qt} < \theta_{Rt}$ for each t and as R is not adopting a climate policy in the baseline while $\omega_Q > 0$, the reduction speed of the fossil share at any t is faster in Q compared to R , i.e. $|\hat{\theta}_{Qt}| > |\hat{\theta}_{Rt}|$. ■

The difference between the fossil shares in the two groups, $\theta_{Rt} - \theta_{Qt}$, is growing in the time period in which R is not adopting any climate policy. In each group, this has an impact on energy prices, which are a function of carbon pricing, technical progress in clean energies, and sectoral factor shares that change over time. We state

Lemma 2 *Energy price development differs between the two groups. In group R , energy is cheaper than in Q during the initial phase, then experiences price growth after the policy tipping point, followed by a price decrease in the final phase; in Q , energy prices grow in a first phase and decrease thereafter.*

Proof. Energy price growth \hat{p}_{Et} is a function of price growth of the two energy types based on Eq. (9). With $\hat{\omega}_R = 0$ before tipping and $\hat{\omega}_Q > 0$ we have

$$\hat{p}_{ERt} = -(1 - \theta_{Rt})\chi < 0 \quad (24)$$

$$\hat{p}_{EQt} = \theta_{Qt}\omega_Q - (1 - \theta_{Qt})\chi \gtrless 0. \quad (25)$$

These expressions reveal that for R , before the policy switch, energy prices are falling over time due to technical progress in clean energies. Energy prices in Q are constant when $\bar{\theta}_Q \omega_Q = (1 - \bar{\theta}_Q)\chi$, increasing for $\theta_Q > \bar{\theta}_Q$ and decreasing for $\theta_Q < \bar{\theta}_Q$. ■

In the quantitative section I will first show the effects when policies remain unchanged throughout and then compare them with the effects of policy tipping. The analysis of expenditure shares and energy prices is the foundation for the result on the policy tipping point, stated in the following

Proposition 1 *Policy tipping in extracting group R occurs in finite time, at the point in time t where the following condition holds*

$$\frac{\theta_{Rt} - \theta_{Qt}}{\theta_{Qt}} = \frac{\omega_Q}{\chi} \quad (26)$$

which says that the difference in the fossil shares between the extractor group R and the protector group Q divided by the fossil share in Q equals the ratio of fossil price growth and productivity growth in the clean energy sector.

Proof. The Appendix shows, that growth of per capita consumption in group j , \hat{C}_j , is given by

$$\hat{C}_{jt} = \frac{(1 - \varepsilon) m \kappa \psi - a \varepsilon}{a \varepsilon} - \frac{1 - a - b}{a} \hat{p}_{Ejt}. \quad (27)$$

This reveals that in each group, long-run per capita consumption growth \hat{C}_t is determined by productivity of the research sector (m) and of education (κ), the intensity of knowledge spillovers (ψ) and the gains from diversification ($(1 - \varepsilon) / \varepsilon$) which all have a positive impact on the growth rate via the innovation rate in the final goods sector, \hat{N} , and energy price growth \hat{p}_{Ej} , which is group-specific and has a negative impact. Positive (negative) energy price growth \hat{p}_E reduces (increases) the consumption growth rate; it is weighted by the factor $(1 - a - b) / a$ that is the ratio of the energy value share in intermediate goods production to the labor share. The difference between growth rates in the two groups Δ then becomes

$$\Delta_t = \frac{1 - a - b}{a} (\hat{p}_{ERt} - \hat{p}_{EQt}) \quad (28)$$

Using Lemma 2 and setting $\Delta_t = 0$ in Eq. (28) provides the result of the Proposition, determining the tipping point condition for a policy shift in R . ■

The outcome allows for two important conclusions. First, climate policies have adverse economic effects only in a first phase of economic development. In a later phase, the positive

impact of technical advances in clean energies are larger in an economy with stringent climate policy. Second, energy prices are important for relative consumption growth.²⁶ The higher speed of decarbonization in Q causes the fossil share to decrease faster than in R , so that technical advances in the clean sector and associated price reductions become increasingly important with the growing share of regenerative energies. At the point of policy tipping, the higher share of clean energies in Q allows to compensate for the price growth of dirty energies, so that growth of energy prices and consumption becomes equal across the groups.

From Proposition 1 it emerges how policy in Q has an impact on R . It is equally relevant to ask how the stance of group R shapes policy formulation in group Q . In public debate, the decreasing motivation of protector countries is a big topic. However, moderating carbon pricing in reaction to R 's lacking policy commitment weakens overall climate policy so that global temperature increase becomes bigger. There are two other policy options for Q : increase of carbon price growth ω_Q or increase of \varkappa_Q to $\tilde{\varkappa}_Q$ through subsidies. The results are stated in the following

Proposition 2 *An increase of carbon price growth in group Q induces faster decarbonization in Q but raises the difference in fossil shares across groups required for policy tipping; subsidies to the clean energy sector in Q induce faster decarbonization in Q and reduce the difference in fossil shares across groups required for policy tipping, so that switching is reached earlier in time, additionally supporting decarbonization.*

Proof. Lemma 1 shows that $\hat{\theta}_Q$ is increasing in ω_Q but Proposition 1 reveals that the tipping point condition $(\bar{\theta}_R - \bar{\theta}_Q) / \bar{\theta}_Q$ is also growing in ω_Q so that the overall impact on the time of policy tipping and decarbonization is ambiguous; Lemma 1 and Proposition 1 equally show that raising \varkappa_Q to $\tilde{\varkappa}_Q$ raises $\hat{\theta}_Q$ but lowers the tipping point condition, so that policy tipping occurs earlier and the impact on decarbonization is unambiguously positive.

■

In the quantitative section I will show graphically the effects of different policies on the point in time when tipping occurs. Energy price development determines relative growth performance of the two groups, which is summarized in

²⁶This is a general feature but emerges as a sharpened outcome of this model. In reality, not only energy but also other sectors like research as well as parameters like research and education efficiency may differ across country groups. However, one would expect that there, the discrepancies would be more persistent whereas energy prices are dynamically changing, inducing changing growth conditions over time.

Proposition 3 *Consumption in extractor group R grows at an increasing rate in a first phase, drops after policy tipping, and converges to the world rate in the long run; consumption in protector group Q grows at a decreasing rate in a first phase and starts to rise when the fossil share reaches the energy price peak, it converges to the world rate in the long run.*

Proof. Use Eqs. (27) (24), and (25) to derive the results. ■

The quantitative section will visualize these effects and show that consumption growth in Q exceeds the rate in R after tipping. Furthermore, consumption level will exceed the level in Q in finite time, revealing the compatibility of climate protection and economic performance in the longer run.

Proposition 4 *Global emissions are decreasing or increasing in a first phase but unambiguously decreasing after policy tipping in extractor countries; the progress of decarbonization depends on technical progress in clean energies and the policy mix implemented by protecting countries.*

Proof. Use Eqs. (12), (6), and (15) to write for emission growth in j

$$\hat{Z}_j = \hat{C}_j + \hat{\theta}_j - \omega_j \quad (29)$$

which shows that, in each group, emissions develop in proportion to consumption growth (scale effect), growth of the fossil fuel share (substitution effect), and price growth of dirty energies (policy effect). Unless a tipping point is reached, we have $\omega_R = 0$, i.e. no policy effect in R , while the scale effect is expected to exceed the substitution effect, see the quantitative application below. In group Q , however, we have $\omega_Q > 0$ and, also due to $\varkappa > 0$, the substitution effect is stronger than in R and thus dominates from the start. ■

Global emissions are the sum of the two groups' emissions; they are increasing or decreasing before policy tipping and strictly decreasing after the tipping point. Whether the global temperature targets can be reached depends on the policy adopted in group R , see the quantitative results below.

4 Quantitative Analysis

I consider the time period 2025 – 2060 and calculate consumption development and emissions per group and worldwide, with a focus on the occurrence of policy tipping and its

consequences. The calibration of the parameter values is presented in Table 1. I use average labor and energy shares of larger economies (OECD 2024), i.e. $a = 0.7$, $b = 0.265$, and $1 - a - b = 0.035$. I assume that training of researchers takes 20 percent of their work time, i.e. $\kappa = 0.8$. Productivity in the research lab m , the knowledge diffusion coefficient ψ , and the mark-up parameter ε are calibrated to match the model with the 2.5% growth of the world economy which was observed on average in the recent years. The reaction of the elasticity of substitution between fossil fuels and regenerative energies β is set at 4, which is the value suggested by Jo and Miftakhova (2024). For the initial value of fossil fuels as a percentage of costs in the energy sector, I subtract the share of primary energy sources from renewables (Our World in Data 2025) from unity. In 2024, the share of renewables was 6% for Russia, 12% for the US, 18% in China, 23% in the EU and 72% in Norway. Below I use a value for 2025 of 88 % for θ_{R0} and 78 % for θ_{Q0} . To obtain the used carbon budget up to 2050, I take the value of 38 GtCO₂ for the 2024 emissions from Friedlingstein et al. (2025) and calculate the subsequent emissions using the present model; the temperatures associated to the different carbon budgets are also provided by Friedlingstein et al. (2025).

ε	m	κ	ψ	a	b	$1 - a - b$	β	γ	θ_{0R}	θ_{0Q}
0.67	3.64	0.8	0.5	0.7	0.265	0.035	4	0.2	0.88	0.78

Table 1: Calibrated values

The different scenarios for adopted policies are displayed in Table 2. In R , carbon price growth $\omega_{R1} = 0$ applies before tipping and $\omega_{R2} = 0.025$ afterwards; in Q , $\omega_Q = 0.025$ is the standard scenario while $\tilde{\omega}_Q = 0.1$ is a possible policy reaction of Q in a divided world. A ten percent annual growth of carbon prices appears to be quite high, but note that here carbon taxes are assumed to include all additional political measures applied in real politics (except subsidies) such as bans (equivalent to a tax with a rate of infinity for the targeted products), norms, or quota (which can also be valued in terms of carbon prices). Productivity in clean energy research is $\chi = 0.05$ in the standard case for both country groups j and $\chi_{low} = 0.025$ in a pessimistic scenario. To do justice to the concerns about possible raw material scarcities for clean energy conversion, these numbers lead to price drops in clean energies that lie substantially below the suggestions of Way et al. (2022). Subsidies to research in group Q may raise the productivity to $\tilde{\chi}_Q$, i.e. $\tilde{\chi}_Q = \chi + s_{\chi Q}$.

ω_{R1}	ω_{R2}	ω_Q	$\tilde{\omega}_Q$	χ_{low}	χ	$\tilde{\chi}_Q$
0	0.025	0.025	0.1	0.025	0.05	0.1

Table 2: Adopted policies

In the following, I am visualizing the main model elements and then show the impact of policy tipping graphically. The first four figures show the development when no policy tipping is triggered, the subsequent graphs compare the no tipping case with the effects of tipping. Supplementing Lemma 1, Figure 1 shows that in both country groups R and Q , expenditures for fossil energies as a share of total energy expenditures decrease over time and that the fossil share decreases faster in the protector countries.

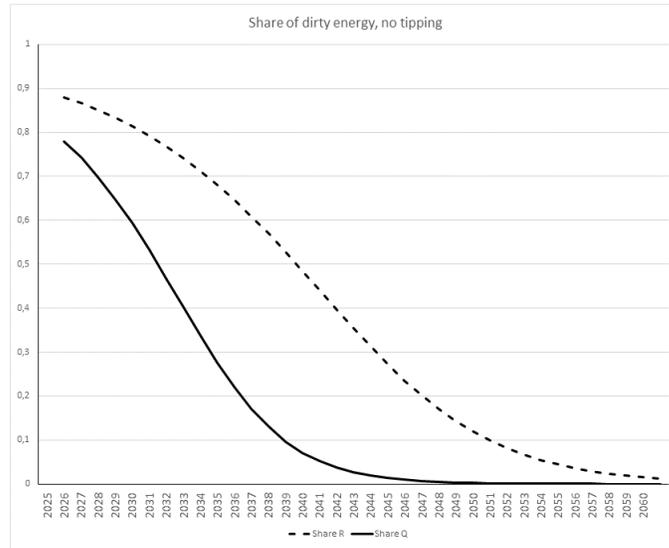


Figure 1: Fossil shares without tipping

Figure 2 displays energy price growth in the two groups revealing that the curves intersect, which gives rise to a (potential) policy tipping point. It demonstrates the first part of the result in Lemma 2, saying that energy in R is relatively cheaper in a first phase and that in Q , energy prices grow in a first phase and decrease thereafter. In the standard calibration, tipping occurs in the year 2030. The curves are drawn under the assumption that policy in R is not tipping but kept throughout.

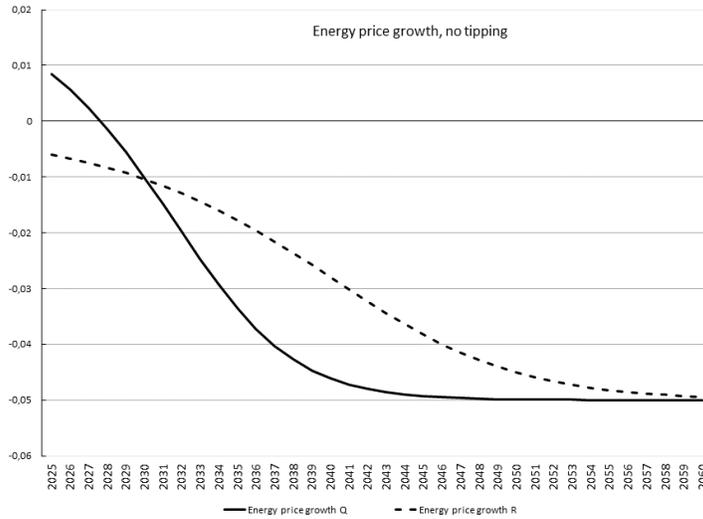


Figure 2: Energy price growth in the two groups, without tipping

Figure 3 shows that consumption growth rate in Q is lagging in a first period relative to Q because of higher energy price growth but then exceeds the growth rate in R as technical advances in clean energies grow in their impact on final output. The figure is drawn for the case where no tipping occurs, the carbon price pattern is kept in the two groups throughout for the whole time period.

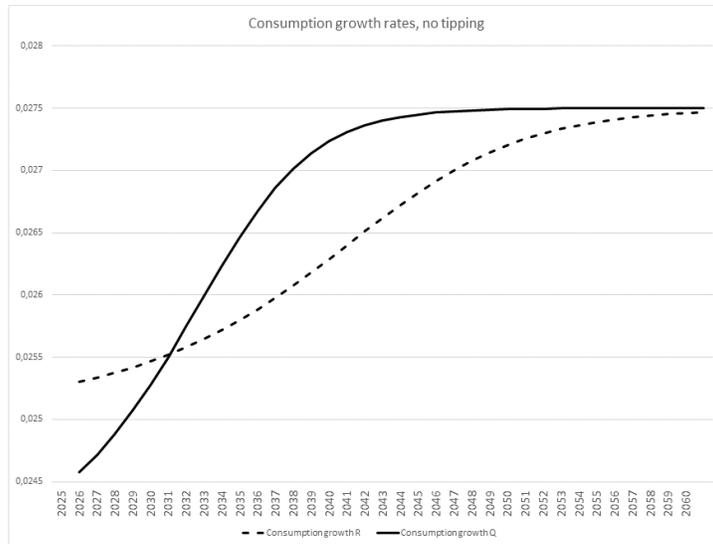


Fig. 3 Consumption growth rates

Figure 4 displays the consumption levels in the two groups, which are normalized to 100 in 2025. From the graphical illustration we can derive two important results. First, the two consumption levels remain very close, despite the big differences in carbon price growth, which is kept constant during the whole time period. Second, while R has a slightly higher consumption level in the beginning, the situation reverses and Q starts to have a higher consumption level from the middle of the period. In 2060, consumption amounts to 249.9 in R and 252.5 in Q .

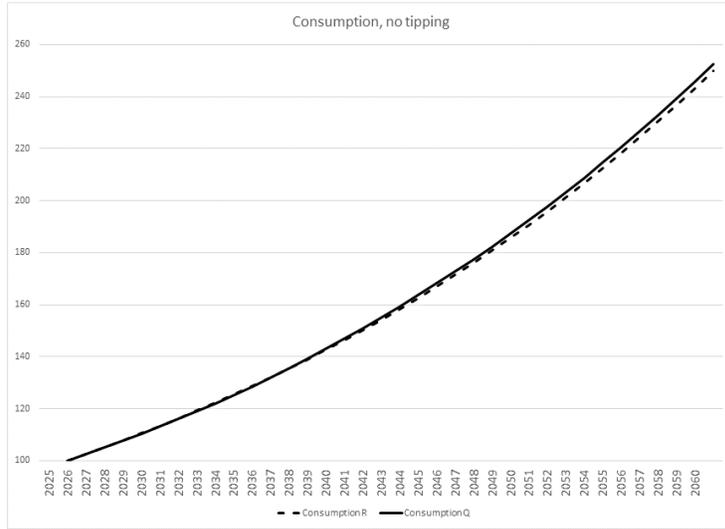


Fig. 4 Consumption without tipping

In contrast to Figure 4, Figure 5 shows consumption development for the case of policy tipping, which in the standard calibration occurs in 2030. The lead of Q becomes a bit more nuanced in this case, but it is remarkable that development remain largely unchanged compared to the no tipping scenario of Figure 4. Here, in 2060, consumption in R amounts to 249.7, which is very slightly lower than without tipping; the final consumption level in Q is unchanged compared to the previous case.

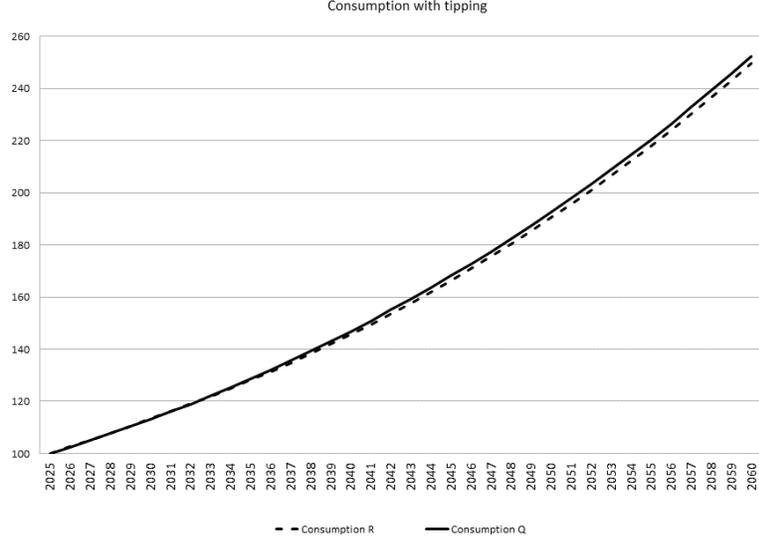


Fig. 5 Consumption with tipping

While consumption does not differ significantly between the two groups and the two policy scenarios, Figure 6 reveals that emissions development is hugely different between the groups. Specifically, due to carbon pricing, decarbonization is stringent and fast in the *Q* group, leading close to zero emissions from 2040 on. In the *R* group, however, the scale effect induces emissions to rise in a first phase while the substitution effect is less strong than in the other country group and policy is missing. Therefore, emissions remain on a significant level in *Q* for two decades. Taking the aggregate of both groups, assuming equal size for the two groups, the use of carbon space amounts to 547 Gt CO₂, see Table 3 on used carbon budget, so that a temperature of 1.8°C is reached with a probability of 67%. The deviation from the 1.5°C target due to group *R* is significant.

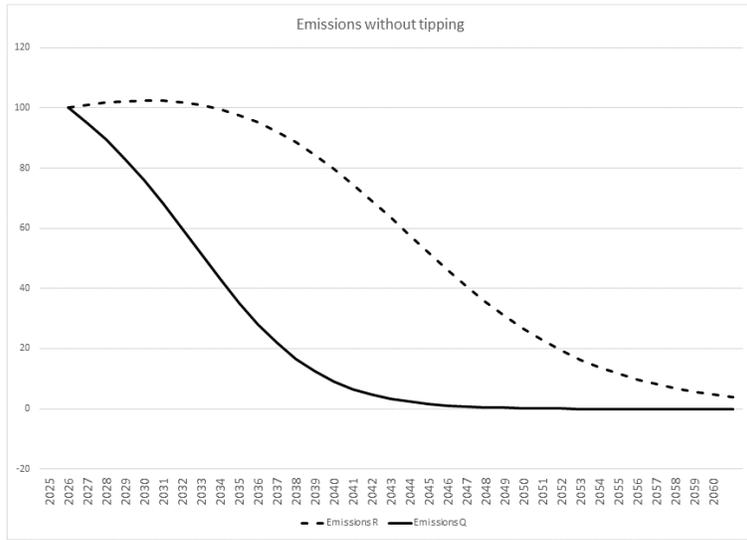


Fig. 6 Emissions without tipping

The significant effect of policy tipping due to systems competition on emissions is shown in Figure 7. It becomes evident that, after policy tipping, the decarbonization path in the *R* group is shifted to the left and has a steeper shape, similar to the one of the *Q* group and converging to zero emissions in the middle of the century. Aggregate emissions are reduced significantly to 413.Gt CO₂ which allows for a temperature target of 1.7°C warming.

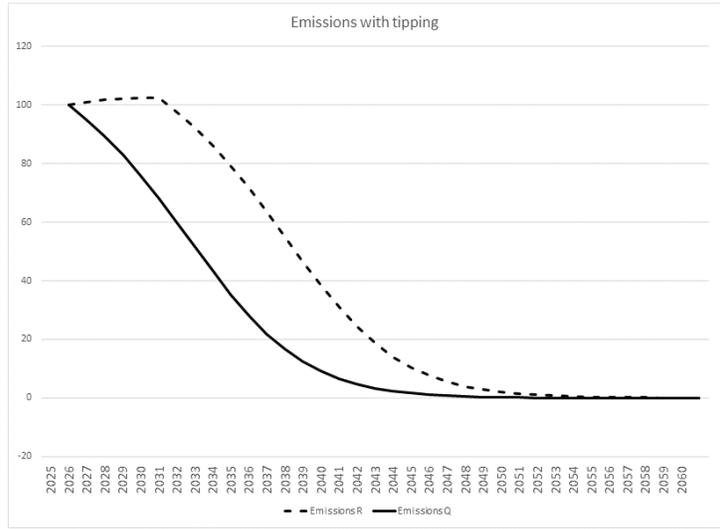


Fig. 7: Emissions with tipping

The absence of climate policy in R does not have a bigger (negative) impact on climate change because technical progress in clean energies is assumed to be steady and strong. This is a well-motivated but critical assumption. It is thus instructive to look at the alternative case with lower progress in the productivity of clean energies ($\alpha_{low} = 0.025$), which is shown in Figure 8. To compare matters to the previous case, the Figure does not include policy tipping. Under these assumptions, it emerges that emissions in the R group do not significantly decline like in previous case of Figure 6. Here, used carbon space until 2060 amounts to 985 Gt CO₂, which does not allow to remain below 2°C warming.

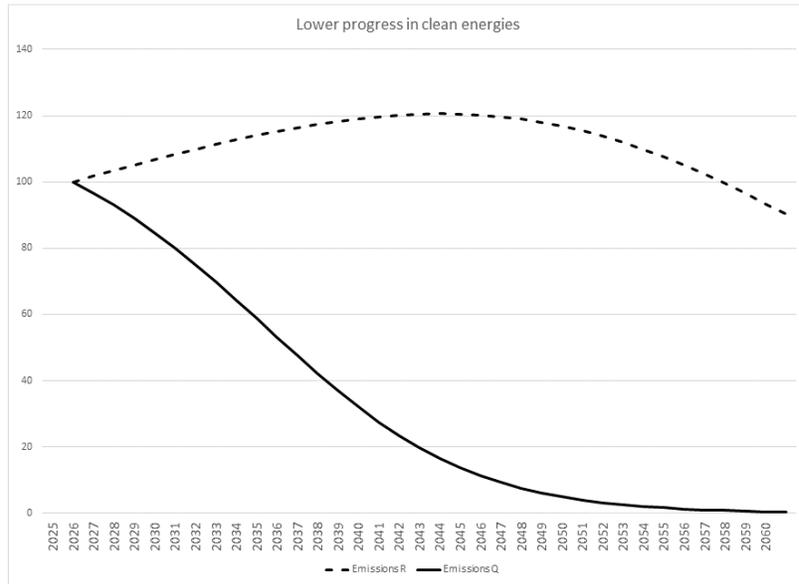


Fig. 8: Emissions development with low progress in clean energies, no tipping

With lower technical progress in clean energies, policy tipping has an even bigger impact on climate change. The difference in emissions to the case without tipping is actually bigger in the scenario with less progress in clean energies, where tipping allows to reduce carbon use to 765 Gt CO₂ and warming to 1.9°C, see Figure 9. Hence, the weaker is technical progress in clean energies, the more important becomes system competition for limiting global temperature increase.

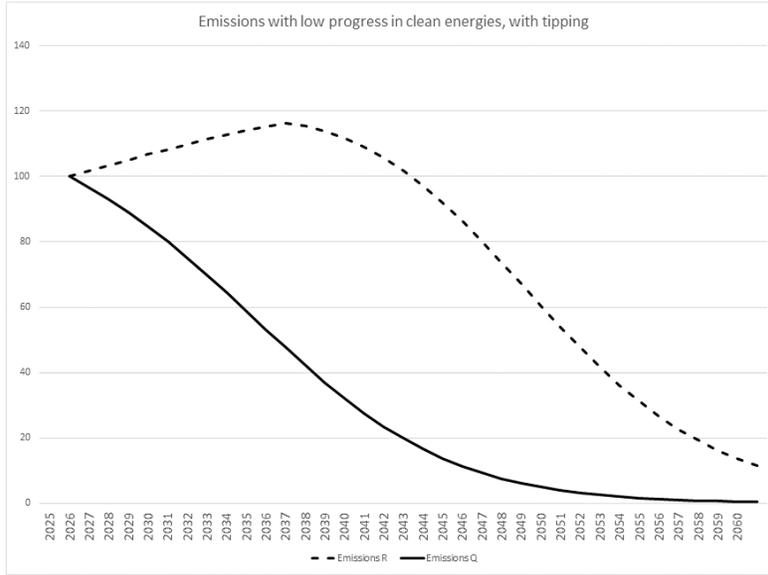


Fig. 9: Emissions development with low progress in clean energies, with tipping

If country group Q aims to implement stricter decarbonization it may consider raising its carbon price growth or its subsidies, which both enforce the substitution effect in the Q group. When system-related policy tipping is active, there is a big difference between the two policy instruments. Higher carbon price growth shifts the tipping point to the right on the time axis, while higher subsidies shift it to the left, so that decarbonization is supported more strongly. Going back to the standard calibration with $\chi = 0.05$, Figure 12 and 13 in the Appendix show the impact of the policy changes on energy price growth in both groups, for the case where carbon price growth rises from 0.025 to 0.1 in Figure 12 and when higher subsidies induce productivity growth in clean energies of 0.1 instead of 0.05 in Figure 13. The figures show that, with higher taxes, the tipping point is postponed from 2030 to 2032, i.e. a delay of 2 years, while it occurs in 2028 with higher subsidies, where it is preponed by 2 years.

Taking policy tipping into account, the effects of higher carbon price growth in Q on emissions in Q and R are shown in Figure 10. Emissions decrease sharply in Q , which accelerates decarbonization, but remain high in R for several years before tipping occurs and induces them to revert and to decline as well. The used carbon budget of Q is reduced to 82 Gt CO₂ but is still 279 Gt for R so that globally we have emissions of 362 Gt CO₂ yielding a temperature target of 1.65°C.

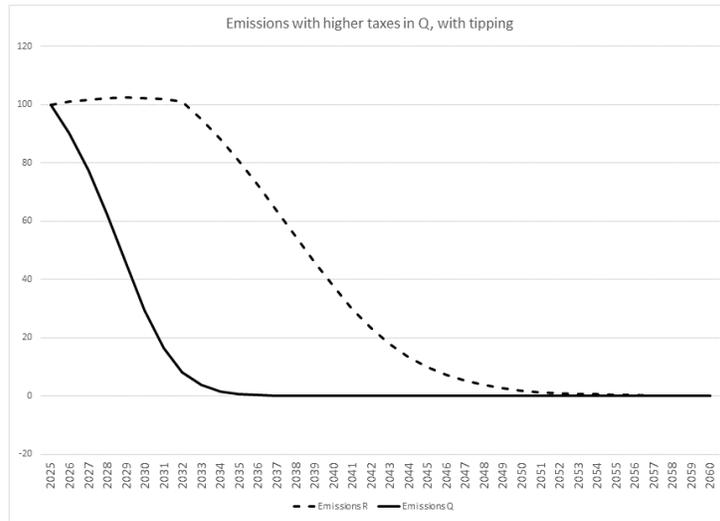


Fig. 10: Emissions with higher carbon taxes and tipping

Figure 11 reveals the effects of higher subsidies to clean energies on emissions in both groups. Like with higher tax growth, decarbonization in Q is accelerated. The graph shows that in R , due to earlier tipping, the emissions path is shifted to the left on the time axis. The earlier start of decarbonization due to policy tipping allow to reduce the used carbon budget significantly. Used carbon budget in Q amounts to 97Gt CO₂, to 238Gt CO₂ in R , and 336 Gt CO₂ worldwide. This is the lowest value analyzed in this paper, allowing to reach a temperature target of 1.6°C with a probability of 67 %.

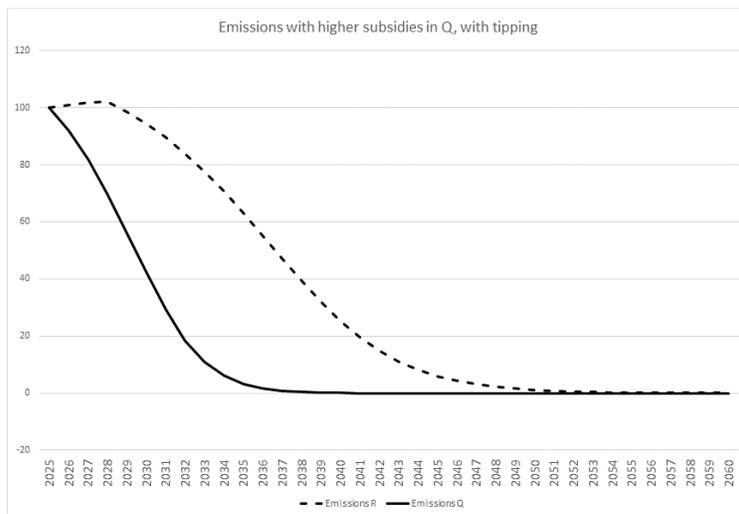


Fig. 11: Emissions with higher subsidies and tipping

The used carbon budget in the time period 2025-2060 and the associated temperature increase that is reached with a probability of 67% in the different scenarios are summarized in Table 3.

Scenario	Budget R	Budget Q	Budget $World$	Temperature
No Tipping				
Baseline case	393	154	547	1.8°C
Low progress clean energy	760	225	985	>2°C
With Tipping				
Baseline case	259	154	413	1.7°C
Low progress clean energy	540	225	765	1.9°C
Higher tax growth	279	82	362	1.65°C
Higher subsidies	238	97	336	1.6°C

Table 3: Used carbon budgets up to 2060 (Gt CO₂)

5 Model extensions

The baseline model can be extended in several ways. The implications of the possible extensions are summarized in this section.

KNOWLEDGE SPILLOVERS BETWEEN THE GROUPS If knowledge spillovers are not only circulating in each group separately but across both groups, total factor productivity increases faster in both groups, which supports consumption growth; also, clean energy pro-

ductivity is affected positively, which promotes decarbonization. In order not to be too optimistic with respect to decarbonization, the present paper abstracts from these additional spillovers.

KNOWLEDGE SPILLOVERS FROM ENERGY TO GENERAL RESEARCH Assuming that research in the final goods sector profits from energy research promotes growth of total factor productivity which, as shown in the paper, is not the main problem during decarbonization; the case is thus disregarded here.

SECTOR SPECIFIC ENERGY KNOWLEDGE When the different energy types do not learn from each other we obtain lock-in situations and can derive conditions for technology tipping, which has been studied extensively in the literature of directed technical change. To stay focused on the main topic of systems competition, the present paper abstracts from technology tipping.

MORE INPUTS IN ENERGY CONVERSION The use of scarce minerals and additional inputs in the conversion of clean energies may slow down price reductions and deployment of renewable energies. In the present paper, this aspect is accommodated by a careful calibration of progress in renewable energies but can be further extended in theory in future work. As it equally applies to both country groups it has an impact on world development but not on systems competition or the tipping point, the focus of this paper.

GOODS TRADE ACROSS THE COUNTRY GROUPS As the model assumes production symmetry between the groups, the motivation for international trade is not evident and trade not regarded here.

ASYMMETRIC INNOVATION ACROSS THE GROUPS Provided that the basic parameters driving innovation, like innovation and education efficiency, differ across the two groups, the policy tipping point occurs earlier or later in time. One could also divide the extractor group R in a high- and a low-productivity subgroup to include more possible scenarios.

COSTS OF POLICIES Actual policy cost is a serious problem in general and, in particular, in environmental economics. In basic pure theory, Pigouvian taxes remove a distortion and come at no cost. In reality, public protests arise regularly when environmental taxes are introduced, revealing that a sufficient number of individuals actually perceive net costs so that political implementation becomes difficult in reality. The benefits of subsidies are highly visible while the cost are less visible to the public; of course, the cost of financing subsidies through taxes or debt have still to be considered in a complete analysis. One could derive political equilibria by introducing limits to rational behavior and limits to

information of voters but this would go far beyond the scope of the present contribution.

6 Conclusions

The study has characterized decarbonization and economic growth for a world hosting a group of countries without active climate policy and another group adopting active policy. The model has been used to calculate each group's economic performance and the consequences of unequal climate policies on global emissions. Furthermore, I have shown how economic growth and global emissions change when system competition between the country groups triggers a tipping point in climate policies. Finally, the model has analyzed the effects of possible policy responses by the protecting group, given the lacking policy commitment of the extracting countries.

As a first result I have derived that economic growth in protecting group Q exceeds growth in extracting group R in finite time so that the assumed condition for policy tipping in extracting group R is always reached. Consumption growth in extractor group R rises in a first phase, drops after policy tipping, and converges to the world growth rate in the long run; consumption in protector group Q grows at a decreasing rate in a first phase and starts to rise when the economy reaches the energy price peak; it converges to the world rate in the long run. The quantitative sections reveals the moderate impacts of climate policy on economic growth and the strong effects on the group's emissions, determining global warming. It calculates the net effects of policy tipping on worldwide emissions, which are significant in the baseline case and even crucial to limit warming when progress in clean energies is slow. Furthermore, the paper has shown that an increase of carbon price growth in group Q induces faster decarbonization in Q but raises the difference in fossil shares across groups required for policy tipping. Subsidies to the clean energy sector in Q induce faster decarbonization in Q and reduce the difference in fossil shares across groups required for policy tipping, so that policy switching is reached earlier in time, additionally supporting decarbonization. Global emissions are decreasing or increasing in a first phase but unambiguously decrease after policy tipping in the R countries; the progress of decarbonization depends on technical progress in clean energies and the policy mix implemented by protecting countries. A combination of significant carbon price growth to reduce emissions directly and clean energy research subsidies to limit energy price growth and induce early tipping by the Q countries is most effective to reach the internationally agreed temperature targets.

In addition to the aspects presented in this paper, an optimal climate policy mix depends on the relative costs of the policies, which have not been explicitly modeled here but could be integrated in future research. Also, a wider set of knowledge spillovers, goods trade, and policy impacts between the groups can enrich the present analysis. Finally, a more detailed analysis of energy conversion including raw materials would open an interesting field for further results.

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7 Appendix

7.1 Model Derivation

PROOF OF PROPOSITION 1 The current-value Hamiltonian for the household problem in group j is

$$H_j = \log C_j - P_t + \mu [r_j V_j + w_j + p_{Dj} E_{Dj} - p_{Cj} C_j], \quad (\text{A.1})$$

where μ_v denotes the costate variable. For a single household, pollution stock P is exogenous. The following first-order and transversality conditions provide the necessary conditions for an interior solution

$$1/c = p_Y \mu, \quad (\text{A.2})$$

$$\dot{\mu}_v = (\rho - r) \mu, \quad (\text{A.3})$$

$$\lim_{\tau \rightarrow \infty} \mu_v(\tau) v(\tau) e^{-\rho(\tau-t)} = 0. \quad (\text{A.4})$$

Combining Eqs. (A.2) and (A.3) yields the Keynes Ramsey rule in Eq. (A.8). To derive the equations in Proposition 1 I use the FOCs and the balanced growth path assumptions as follows. First, I adopt the symmetry of intermediate goods in final goods production (Eq. 13) and take the logarithmic differentials to write

$$\hat{Y}_j = \left(\frac{1-\varepsilon}{\varepsilon} \right) \hat{N}_j + \hat{X}_j \quad (\text{A.5})$$

Based on Eq. (14), I have

$$\hat{X}_j = a \hat{L}_{Xj} + b \hat{K}_j + (1-a-b) \hat{E}_j. \quad (\text{A.6})$$

Inserting and using $\hat{Y}_j = \hat{K}_j = \hat{C}_j$, $\hat{L}_{Xj} = \hat{L}_j = 0$, which arise due to the logarithmic utility function, I write for the growth rate of per-capita consumption \hat{C}

$$\begin{aligned} \hat{C}_j &= \left(\frac{1-\varepsilon}{\varepsilon} \right) \hat{N}_j + b \hat{C}_j + (1-a-b) \hat{E} \\ (1-b) \hat{C}_j &= \left(\frac{1-\varepsilon}{\varepsilon} \right) \hat{N}_j + (1-a-b) (\hat{C} - \hat{p}_E) \\ \hat{C}_j &= \left(\frac{1-\varepsilon}{a\varepsilon} \right) \hat{N}_j - \left(\frac{1-a-b}{a} \right) \hat{p}_E. \end{aligned} \quad (\text{A.7})$$

To obtain the innovation rate, I use Eq. (16) and labor market clearing Eq. (19) and apply $L_t \equiv 1$ to obtain for innovation rate \hat{J}_t

$$\hat{N}_j = m\kappa\psi (1 - L_{Xt})$$

Including labor input in the X -sector from Eq. (21) and using the wage rate of Eq. (18) yields an expression for the innovation rate which is inserted into Eq. (A.7) to yield Eq. (27) in the Proposition 1.

PROOF OF PROPOSITION 4 From intertemporal optimization, I obtain first order conditions for the decentralized economy which can be solved to obtain an expression for consumption growth according to the familiar Keynes-Ramsey rule

$$\hat{p}_{Ct} + \hat{C}_t = r_t - \rho. \quad (\text{A.8})$$

Cumulative capital is foregone final output. Given the log-utility function we have $\hat{K}_t = \hat{Y}_t = \hat{C}_t$. The economy develops thus along a path where total output, consumption, and capital stock grow at the same rate that is not necessarily constant.²⁷ I adopt the convention to use the final good as the numeraire so that $p_Y = p_C \equiv 1$. Then, from Eq. (A.8) I have $\hat{C}_t = r_t - \rho$ and from Eq. (15) it follows for emissions growth that

$$\hat{Z}_t = \hat{C}_t - \hat{p}_{Et}. \quad (\text{A.9})$$

7.2 Additional Figures

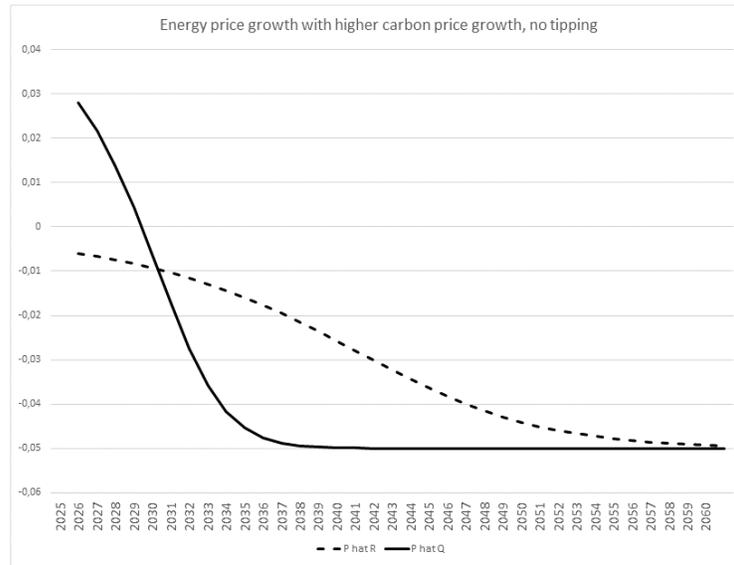


Fig. 12: Energy Price growth with higher carbon pricing

²⁷In the innovation-driven model adopted here the climate damage on physical capital is a level effect so that it does not show in the growth equations of the paper.

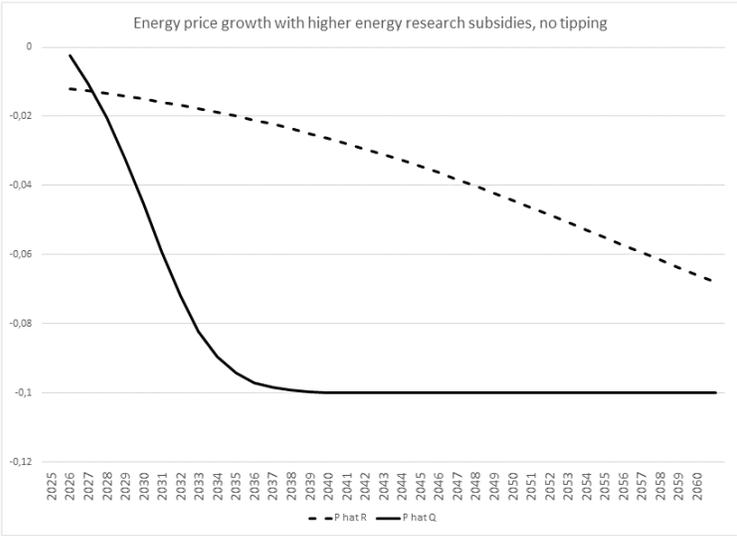


Fig. 13: Energy prices with higher subsidies